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The research performed in this study focused on improved tungsten heavy alloys through process optimization as measured by affects on microstructure and impurity concentrations. This largely was performed by alloying and adjusting the sintered microstructure through processing changes. Many past heavy alloy studies have failed to couple the two activities. As a consequence, potentially beneficial alloying effects have been masked by incomplete densification. Alternatively, novel processing approaches have been unsuccessful because they were applied to conventional alloys. This research has advanced both aspects, leading to novel heavy alloys with tantalum, rehnium, or molybdenum alloying.

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Microstructure and Impurity Effects on Tungsten Heavy Alloys

Final Report

Randall M. German

July 1990

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Rensselaer Polytechnic Institute
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Microstructure and Impurity Effects

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Final Report

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for the period from 1 May 1987 to 30 April 1990

from

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Introduction

Tungsten heavy alloys exhibit the unique property combinations of high strength, ductility, density, and toughness. These alloys are typically fabricated by liquid phase sintering mixed elemental powders. The resulting product is a composite consisting of interconnected tungsten grains with an interpenetrating solidified liquid phase. A typical composition is 90 to 95% tungsten with a nickel to iron ratio of 8:2 or 7:3. Although the alloys have been in use for over fifty years for gyroscopes, counterbalances, semiconductor substrates, radiation shields, and machining tools, the primary recent activity has been related to military applications. These include projectiles, shape charge liners, and armour. In these applications the main concerns are with the strength, hardness, and toughness. Usually, the needed strength and hardness are created by selective deformation and heat treatment after sintering (for example by a swage and age treatment). Unfortunately, this denies net shape fabrication which is a desirable aspect of powder metallurgy fabrication.

It is evident that the low strain rate, room temperature mechanical properties are only approximate guides to the success of the military components. Circumstantial evidence suggests that superior properties might result from very small grain size compacts [1-5]. However, normal sintering practice involves a prolonged hold above the liquid formation temperature, leading to considerable microstructural coarsening. Although the resulting ductility is high, the strength is low with the large grain size material. The alternative is to sinter for shorter times

with smaller initial particle sizes, but this has not proven successful because of problems with powder availability, contamination, poor densification, and rapid microstructural coarsening. Thus, the inherent manufacturing route for heavy alloys is to sinter to full density in a prolonged cycle that gives a large final grain size. Subsequently, the compact is deformed and heat treated to increase the strength at the expense of the ductility.

The research performed in this study focused on improved tungsten heavy alloys through process optimization as measured by affects on microstructure and impurity concentrations. This largely was performed by alloying and adjusting the sintered microstructure through processing changes. Many past heavy alloy studies have failed to couple the two activities. As a consequence, potentially beneficial alloying effects have been masked by incomplete densification. Alternatively, novel processing approaches have been unsuccessful because they were applied to conventional alloys. This research has advanced both aspects, leading to novel heavy alloys with tantalum, rhenium, or molybdenum alloying. This has led to patents on new heavy alloy compositions [6-8]. A key aspect of the research has been to coordinate the activities on microstructure refinement, densification, alloying, and processing. As an example of the importance of this coupled activity, consider that research on rhenium additions to tungsten heavy alloys was reported by Dickinson et al. [9] in 1974. They used a constant processing cycle for all alloying studies and failed to note the significant benefits possible. In contrast, we determined that a variation in the sintering cycle was necessary with alloying to attain the full benefits and improved properties [10]. Consequently, significantly improved properties were observed in the latter study which were overlooked in the earlier investigation.

This research created a fundamental understanding of liquid phase sintering, alloying, powder processing, and microstructure-property relations for tungsten heavy alloys. The alloying work focused on rhenium, molybdenum, and tantalum additions, and considered possible important effects from the impurities such as oxygen, carbon, and nitrogen. The refractory metal additives have decreased the sintered grain size by interfering with the solution-reprecipitation process during liquid phase sintering. The strengthening role of these alloying additions is through solid-solution strengthening and grain growth inhibition. Thus, small quantities of these additives are potent in controlling grain growth during sintering. The experimental matrix included parallel examinations of the processing cycle for optimization. This included atmosphere, time, temperature, heating rate, cooling rate, deformation, and heat treatment parameters. Progress in this area was aided by application of an analytical sintering furnace developed for sintering cycle optimization. The success of this approach was determined by measurements of density, microstructure, hardness, strength, ductility, toughness, work

hardening, and aging behavior. From this research emerged significant improvements in the available properties and improved understanding of heavy alloys.

Research Accomplishments

Research in refractory metal processing by enhanced sintering techniques has been supported by ARO at RPI for the past nine years. The first project involved the sintering of molybdenum alloy composites. The second project looked into the basic fracture process and processing of tungsten heavy alloys, while the current project deals with microstructure-impurity interactions in heavy alloys. This has been productive research as evidenced by the attached list of publications and presentations in the Appendix (2 Ph.D. theses, 4 M.S. theses, 3 patent applications, 38 publications, and 35 presentations). Indeed, this body of literature is the best overall documentation of the research conducted at RPI on tungsten heavy alloys.

The ductility and other mechanical properties of heavy alloys are extremely sensitive to impurity segregation, hydrogen embrittlement, residual porosity, and intermetallic phase formation, which can be controlled through processing [11]. As a consequence some general processing guidelines have been established for obtaining optimal properties [1,2,12]. The recent efforts have focussed on improving the strength and hardness at the expense of ductility [13]. Additionally, there have been attempts to improve the properties beyond those attainable with optimized processing of conventional compositions. Of direct relevance are various alloying studies involving Re, Co, Ti, Pt, Mo, Cr, and Al additions [6-21]. Unfortunately, there has been little success from the prior alloying studies due to two main problems; interfacial precipitation or poor processing. There is an extreme dependence of the properties on the processing conditions [11,12,18]. An understanding of alloying effects and optimal processing conditions are mandatory for improved properties. Further, a clear link has been established between mechanical behavior and the strength of the tungsten-tungsten grain boundaries and the tungsten-matrix interface [22,23]. The bulk of these alloying efforts have been unsuccessful because of preferential precipitation at interfaces, which usually embrittles a heavy alloy composite [24-27].

Refinement of the tungsten grain size through alloying additions is another way of improving the strength and hardness of heavy alloys. This route has been largely ignored in previous research. In the ARO research at RPI, alloying additions were selected for both solid-solution strengthening and grain size reduction. When these additions are combined with an optimized processing cycle, higher strength heavy alloys are produced [6-8,10,13,18]. The

properties are similar to conventional heavy alloys subjected to post-sintering deformation and aging. This early progress provides a promise of further improvements. With improved understanding it is envisioned that higher performance materials can be gencrated by alloying and process control.

Examples of the average mechanical properties of a 90% tungsten plus additive heavy alloys (10% matrix) with molybdenum, tantalum, or rhenium additions are summarized in Table 1. The elongation decreases monotonically with increasing alloying. Increasing the sintering time from 30 minutes to 120 minutes for molybdenum containing alloys reduces the ultimate strength by approximately 60 to 80 MPa while increasing the elongation by 5 to 9%. Similar changes with extend sintering time are observed with traditional heavy alloys due to grain coarsening. The increase in the strengths due to rhenium are quite dramatic. In contrast, the full potential of tantalum as an alloying addition has not been achieved due to residual porosity, possibly associated with tantalum's affinity for hydrogen. This is an obvious area for further research and process development.

The increased strength is due to the combined effects of solution hardening and grain refinement. This is confirmed by statistical comparison of grain size effects on strength and microhardness measurements. Rhenium is very potent in reducing grain size, as is evident by the smaller grain size and more irregular grain shape. The grain size and solid-solution strengthening factors cause a continuous increase in the hardness with increasing refractory metal additions. During cooling the the additives come out of solution from the matrix, allowing precipitation hardening. Accordingly, considerable strengthening lies untapped in the modified heavy alloys through combined alloying and processing studies.

Many refractory metals are soluble in both tungsten and the matrix phases; thus, they provide solid-solution strengthening. Also microstructural coarsening is reduced by the presence of a second solid phase during liquid phase sintering [28]. The grain growth law for liquid phase sintered heavy alloys is as follows:

$$G^3 = G_o^3 + K\,t \qquad (1)$$

where G is the grain size after an isothermal hold for time t, with the initial grain size at $t = 0$ given by G_o. The parameter K depends on the material constants [29],

$$K = g\,D\,C\,V\,S\,/\,[k\,T\,(1 - f^{1/3})] \qquad (2)$$

where g is a geometric constant, D is the diffusivity, C is the solubility, V is the atomic volume, S is the interfacial energy, k is Boltzmann's constant, T is the absolute temperature, and f is the volume fraction of solid. A reduction in the solubility of tungsten in the liquid results in a smaller sintered grain size. The sintered strength is improved, both by a smaller grain size and by alloying. Furthermore, a lower dislocation mobility provides the possibility of exceptional strength for heavy alloys if the sintered grain size can be further reduced [30].

Microprobe measurements were performed to isolate the distribution of the additive in the sintered alloys. These results evidence nearly equal partitioning between the matrix and the grains. Closer analysis of individual particles shows the additive content is high in the particle center and decreases toward the particle edge. These observations indicate the additive is preferentially in solution early in the sintering process. Accordingly, it retards (via a displacement reaction) the tungsten grain growth. The sintered grain size and shape depend on the cooling rate from the sintering temperature. Rapid cooling results in rounded tungsten grains with considerable post-sintering age hardening potential. Alternatively, slow cooling gives a mixture of rounded and irregular tungsten grains, and two phases in the matrix. When the matrix phase is prealloyed with molybdenum, sintering densification is not affected adversely, yet grain growth in sintering is greatly retarded. In one set of experiments, a full density composition of 82 W - 8 Mo - 7 Ni - 3 Fe resulted in a sintered tungsten grain size of 3.8 μm. This is very significant considering that the initial tungsten particle size was 2.5 μm. In contrast, the equivalent alloy without molybdenum will have a sintered grain size over 60 μm.

One advantage from this research is that higher performance alloys can be processed to net shapes. Heavy alloys requiring high strength and hardness are normally obtained by post-sintering deformation and aging which prevents the use of net shape processing. The strength levels obtained by alloying are comparable to those obtained by deformation of traditional heavy alloys [13,31,32]. Injection molding is an emerging process which fully utilizes the near net shape capability of powder processing. Therefore, the properties of injection molded 82 W - 8 Mo - 8 Ni - 2 Fe were determined and are included in Table 1 to demonstrate that such a process is possible. Indeed, injection molding is a viable forming approach for these new heavy alloy compositions.

Thus, this research has determined an optimized processing cycle and demonstrated unique property combinations are possible through refractory metal additives like molybdenum, tantalum, and rhenium. These additives result in increased strength and hardness and decreased ductility; a classic trade-off between strength and ductility. In all cases, the additive results in

grain size refinement by the modification of the solution-reprecipitation stage of sintering. Most of the refractory elements have densities which are substantially lower than tungsten, which is a disadvantage in some heavy alloy applications. Rhenium was studied as an alloying addition because it has a density greater than that of tungsten and a high solid-solution strengthening potential due to its small atomic size [10]. The other important attribute is the more extensive grain refinement observed with the rhenium alloying. The highest strengthening results from rhenium additions and the grain refinement effect is remarkable. Because the density of rhenium is 21 g/cm^3, its addition to a heavy alloy increases the composite density. Rhenium has some solubility in tungsten and a high solubility in nickel at the liquid phase sintering temperature. Thus, rhenium refines the microstructure, provides solid-solution strengthening, and increases the alloy density. For an alloy with a composition of 84 W - 6 Re - 8 Ni - 2 Fe, the sintered density was 17.4 g/cm^3 with a sintered yield strength of 815 MPa, tensile strength of 1183 MPa, and elongation to failure of 13%. This property combination results from the aggregate effects of grain size reduction and solid-solution hardening due to rhenium.

Much success has taken place through improved processing, but parallel compositional studies have resulted in new microstructure-property combinations. As part of these investigations the Ni/Fe ratio has been varied, with the general conclusion that optimal strength and ductility occurs with a ratio between 2 to 4 [33,34]. Brittle intermetallic phases can form outside of this composition range [35]. Historically, a 7/3 Ni/Fe ratio has been selected for processing studies [36-38]. Recently, Spencer and Mullendore [32] reported higher ductilities and impact energies for 90 and 93% tungsten heavy alloys with the 8/2 Ni/Fe ratio.

The alloy composition has been varied in the nickel/iron ratio and molybdenum was partially substituted for tungsten. The sintered tensile properties were assessed versus these compositional variations. Table 1 summarizes the average results of the experiments. For comparison purposes, the tensile strength for a 90 W - 7 Ni - 3 Fe alloy is 923 MPa with a failure elongation of 30% [39-41]. The yield strength increases linearly with the molybdenum content, and is higher for the 7/3 Ni/Fe ratio. There is a higher yield strength at 90 W - 0 Mo for the 8/2 Ni/Fe ratio, but at all other compositions the 7/3 ratio gives a slightly higher strength. The 8/2 Ni/Fe ratio provides a higher elongation at all compositions.

Statistical analysis of these results showed that all of the properties were significantly influenced by the additive content (confidence of 99%). Further, hardness was an excellent predictor of strength and had an inverse correlation with ductility. Both the yield strength and elongation exhibited a dependence on the Ni/Fe ratio. The 8/2 Ni/Fe ratio gives higher ductility

at yield strengths below 800 MPa, but requires more additive for equivalent strengthening.

The results are best interpreted by examination of the alloying effects on the microstructure. Tungsten solubility in the matrix increases with a higher nickel content. In turn, the rate of grain growth during liquid phase sintering is dependent on the tungsten solubility in the matrix [28]. By increasing the Ni/Fe ratio, there is more solubility for tungsten in the matrix, giving a slightly larger grain size with a lower contiguity. Both factors contribute to a higher ductility and lower strength [40,42-44]. Similar behavior is attained with changes in the sintering temperature, since there are concomitant increases in solubility, grain growth kinetics, and sintered grain size that lead to greater ductility and lower strength [22]. The current findings indicate the Ni/Fe ratio effect on tensile properties is small in comparison with the role of refractory metal alloying, but there is some benefit from the 8/2 Ni/Fe ratio.

Summary

The hypothesis that emerges from this research is that certain refractory alloying additions to classic tungsten heavy alloys preferentially go into solution during heating. This preferential dissolution of molybdenum, tantalum, or rhenium then inhibits tungsten solubility in the liquid at the sintering temperature, thereby contributing to slower grain growth. Since the total amount of liquid phase is sufficient for densification, the product is dense but smaller in grain size. Accordingly, there is grain size strengthening. Additionally, alloying gives solid-solution or age hardening effects. Thus, heating rate and alloying level are control parameters. Possibly, the preferential coating of the tungsten powder with the alloying addition is a means of further inhibiting the uptake of tungsten into the matrix. This will allow large grain size reductions with much lower quantities of additive. Likewise, milling or the reduction of the initial particle size can alter the basic dissolution events during heating and give the desired refinement of the sintered microstructure. Hence, variations in the initial powder characteristics may provide major product changes with minimal alloying or additional processing steps.

The experiments conducted in this research have identified the mechanism for controlling the grain size in the consolidated product [44-46]. Sintered grain sizes of 3.8 μm have been generated in a tungsten heavy alloy fabricated with molybdenum additions. Further the alloying with mixtures of tantalum, rhenium, and molybdenum will provide unique combinations of substitutional solid-solution strengthening and precipitation hardening for both the tungsten and matrix phases. The performance attributes of these doped heavy alloys need to be correlated with composition and processing changes. Performance assessment is beyond the mechanical

property testing performed at room temperature at slow strain rates in this research. The wide range of possible microstructures provide a means of linking performance to the several processing factors (powder characteristics, alloying, sintering, and heat treatments).

There is a need to confirm the mechanism by which such alloying additions inhibit grain growth during liquid phase sintering. Likewise, improved understanding of the strengthening process with these same additions is needed. With this understanding, it will be possible to determine the appropriate amount and placement of the additions to maximize their effects and minimize the concentrations.

To achieve these goals, experiments with various levels of alloying and various techniques for introducing the alloying are being conducted. For example, with molybdenum it is appropriate to alter the content of molybdenum, tungsten, nickel, and iron. Further, early experiments with heavy alloys show some surprising oxygen activity changes during heating [47-48]. The master program of temperature-time-atmosphere is derived from a computer control system that analyzes these signals and determines the appropriate changes in sintering conditions. With closed-loop feedback controlled sintering, major changes in the sintering response can be accommodated with minimal experimentation.

The evidence for inhibited grain growth due to refractory metal additions is very strong [6-8,10,13,18,38]. Further, these systems have great potential for precipitation hardening, post-sintering deformation, and strain aging. Experiments need to be performed on selected systems to specifically develop high sintered hardnesses. These experiments are in progress on various annealing and heat treatment cycles, and will include deformation as appropriate. Attention is being directed specifically to precipitation control in the microstructure, especially the tungsten-matrix interface which is most sensitive to heterogeneous precipitation.

Table 1

Example Tungsten Heavy Alloy Properties from This Research

additive wt. %	Ni/Fe ratio	yield strength, MPa	tensile strength, MPa	elongation, %	hardness HRA
0	7/3	534	923	30	63
0	8/2	551	918	36	64
4 Mo	7/3	625	978	24	64
4 Mo	8/2	598	947	31	64
8 Mo	7/3	715	1030	20	66
8 Mo	8/2	688	1048	24	66
12 Mo	7/3	835	1103	10	68
12 Mo	8/2	773	1119	14	67
16 Mo	7/3	892	1145	07	69
16 Mo	8/2	843	1150	10	68
0 *	7/3	1315	1420	02	73
4 Mo*	7/3	1345	1440	01	73
8 Mo*	7/3	1390	1510	01	74
5 Ta	7/3	740	1025	03	69
4 Re	7/3	732	1050	07	69
2 Re	8/2	703	1036	17	66
4 Re	8/2	766	1118	14	67
6 Re	8/2	815	1183	13	69
8 Mo#	8/2	770	1115	20	64

* = swaged and aged
# = injection molded

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Appendix

Research Results from ARO Funding

Theses

P. E. Zovas, "Retarded Grain Boundary Mobility in Activated Sintered Molybdenum," M. S. Thesis, Rensselaer Polytechnic Institute, Troy, NY, May 1983.

M. R. Eisenmann, "Factors Influencing Ductility and Fracture Strength in W-Ni-Fe Alloys," M. S. Thesis, Rensselaer Polytechnic Institute, Troy, NY, May 1983 (partially supported by ARO).

L. L. Bourguignon, "Microstructure - Impurity Interactions in Tungsten Heavy Alloys," M. S. Thesis, Rensselaer Polytechnic Institute, Troy, NY, August 1985 (partially supported by ARO).

B. H. Rabin, "Microstructure and Tensile Properties of Liquid Phase Sintered Tungsten-Nickel-Iron Composites," Ph. D. Thesis, Rensselaer Polytechnic Institute, Troy, NY, December 1986.

S. Farooq, "Theory of Liquid Phase Sintering: Model Experiments on the Tungsten-Nickel-Copper Heavy Alloy System," Ph. D. Thesis, Rensselaer Polytechnic Institute, Troy, NY, May 1988.

P. Kemp, "The Role of Additives on the Microstructure and Properties of Tungsten Heavy Alloys," M. S. Thesis, Rensselaer Polytechnic Institute, Troy, NY, December 1989.

Patent Applications

"High Strength, High Hardness Tungsten Heavy Alloys with Molybdenum Additions and Method," R. M. German, A. Bose and D. Sims, U.S. Patent 4,801,330, 31 January 1989.

"Improving the Hardness and Strength of Heavy Alloys by Addition of Tantalum," A. Bose and R. M. German, U.S. Patent 4,851,042, 25 July 1990.

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A. Bose and R. M. German, "Microstructural Refinement of W-Ni-Fe Heavy Alloys by Alloying Additions," *Metallurgical Transactions*, 1988, vol. 19A, pp. 3100-3103.

R. M. German, S. Farooq and C. M. Kipphut, "Kinetics of Liquid Phase Sintering," *Materials Science and Engineering*, 1988, vol. A105, pp. 215-224, also reprinted in *Science of Hard Materials*, vol. 3, V. K. Sarin (ed.), Elsevier, New York, NY, 1989, pp. 215-224.

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A. Bose, G. Jerman and R. M. German, "Rhenium Alloying of Tungsten Heavy Alloys," *Powder Metallurgy International*, 1989, vol. 21, no. 3, pp. 9-13.

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A. Bose and R. M. German, "Matrix Composition Effects on the Tensile Properties of Tungsten-Molybdenum Heavy Alloys," *Metallurgical Transactions*, 1990, vol. 21A, pp. 1325-1327.

R. M. German, A. Bose, P. B. Kemp, and H. Zhang, "Additive Effects on the Microstructure and Properties of Tungsten Heavy Alloy Composites," *Advances in Powder Metallurgy*, 1989, vol. 2, pp. 401-413.

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A. Bose, H. Zhang, P. Kemp, and R. M. German, "Injection Molding of Molybdenum Treated Tungsten Heavy Alloy," *Advances in Powder Metallurgy*, 1990, in press.

Presentations

"Enhanced Sintering Treatments," invited seminar, joint meeting Connecticut Sections APMI and AIME, Ansonia, CT, October 1983.

"Criteria, Mechanisms and Behavior of Advanced Sintering Methods," invited seminar, Corporate Research and Development Center, General Electric Corp., Schenectady, NY, October 1983.

"Enhanced Sintering Through Second Phase Additions," invited seminar, GTE Laboratories, Waltham, MA, May 1984.

"The Properties of Tungsten Processed by Sintering Techniques," invited seminar, Army Materials and Mechanics Research Center, Watertown, MA, May 1984.

"Analysis of High Tungsten Content Heavy Alloys," Powder Metallurgy in Defense Technology, Picattiny Arsenal, Rockaway, NJ, September 1984.

"Enhanced Sintering Through Second Phase Additions," keynote presentation, Powder Metallurgy

Group Meeting on Sintering Theory and Practice, The Metals Society, Harrogate, UK, October 1984.

"Enhanced Sintering Treatments," invited seminar, Crucible Materials Research Center, Pittsburgh, PA, October 1984.

"Enhanced Sintering Treatments - Activated and Liquid Phase Sintering," invited seminar, Department of Materials Engineering, Drexel University, Philadelphia, PA, November 1984.

"Microstructural Model for Liquid Phase Sintered Materials," invited presentation, 114th Annual Meeting AIME, New York, NY, February 1985.

"Liquid Phase Sintering Fundamentals," invited technical seminar, Northeast University of Technology, Shenyang, Peoples Republic of China, May 1985.

"Microstructure Limitations of High Tungsten Content Heavy Alloys," Eleventh International Plansee Seminar, Reutte, Austria, May 1985.

"Metallurgy of Tungsten Heavy Alloys," technical seminar, California Research and Technology, Pleasanton, CA, July 1985.

"Liquid Phase Sintered Tungsten Heavy Alloys," invited seminar, Sandia National Laboratories, Livermore, CA, July 1985.

"Processing of Tungsten Heavy Alloys," invited seminar, U.S. Army Armament Research and Development Center, Dover, NJ, November 1985.

"A Status Report on Liquid Phase Sintering," keynote lecture, Third Israel Materials Engineering Conference, Haifa, Israel, December 1985.

"Properties of Tungsten Heavy Alloys," invited seminar, Ashot-Ashkelon Industries, Ashkelon, Israel, December 1985.

"Advanced Liquid Phase Sintering Techniques," invited presentation at the Powder Processing Symposium, Oak Ridge, TN, April 1986.

"Theoretical Overview of Activated Sintering and Liquid Phase Sintering," invited presentation, American Society for Metals, Materials Week, Orlando, FL, October 1986.

"Test Temperature and Strain Rate Effects on the Properties of Tungsten Heavy Alloys," presented at the 1986 Fall Meeting of the Metallurgical Society of AIME, Orlando, FL, October 1986.

"Properties and Microstructure of Liquid Phase Sintered Coarse Two Phase Alloys," Institute fuer Werkstoffwissenschaften, Max Planck Institute, Seestrasse, Stuttgart, FRG, 6 April 1987.

"Fundamentals and Applications of Liquid Phase Sintering," visiting scientist lecture series, University of Alabama, Birmingham, AL, 17 July 1987.

"An Update on the Theory of Liquid Phase Sintering," invited presentation, Sintering '87, Tokyo, Japan, 5 November 1987.

"The Kinetics of Liquid Phase Sintering," keynote presentation, Third International Conference on the Science of Hard Materials, Nassau, Bahamas, 11 November 1987.

"Microstructure and Properties of High Tungsten Content Heavy Alloys," invited seminar, Mechanical Engineering Department, University of Texas, Austin, TX, 28 January 1988.

"Basics and Applications of Liquid Phase Sintering," invited seminar, Materials Science and Engineering Department, North Carolina State University, Raleigh, NC, 2 November 1988.

"Advances in Liquid Phase Sintering," invited seminar, Technical Vitality Program, IBM Corp., East Fishkill Facility, Hopewell Junction, NY, 13 February 1989.

"Contiguity and Volume Fraction Effects on Grain Growth Kinetics in Liquid Phase Sintering," presented at the 1989 AIME Annual Meeting, Las Vegas, NV, 27 February 1989.

"Additive Effects on Microstructure and Properties of Tungsten Heavy Alloys," presented at the 1989 AIME Annual Meeting, Las Vegas, NV, 27 February 1989.

"Liquid Phase Sintering," invited seminar, Department of Mechanical Engineering, University of Rochester, Rochester, NY, 15 March 1989.

"Fundamentals of Liquid Phase Sintering as Applied to Tungsten Heavy Alloys," invited seminar, Research Institute of Science and Technology, Pohang, Korea, 19 June, 1989.

"Recent Advances in Strengthening Tungsten Heavy Alloys," invited seminar, Agency for Defense Development, Taejeon, Korea, 20 June 1989.

"Liquid Phase Sintering," invited presentation, Sintering Seminar, Powder Metallurgy Equipment Association, Cincinnati, OH, 24 October 1989.

"Basics and Applications of Liquid Phase Sintering," invited technical seminar, Alcoa Technical Center, Alcoa Center, PA, 7 November 1989.

"Liquid Phase Sintered Tungsten Heavy Alloys," invited NATO seminar presented 6 February 1990

"Tungsten Heavy Alloys for Kinetic Energy Penetrators," invited keynote presentation, Workshop on Tungsten Heavy Alloys, Army Research and Development Command, Dover, NJ, 17 April 1990.